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Review on alcohol fumigation on diesel engine: A viable alternative dual fuel technology for satisfactory engine performance and reduction of environment concerning emission

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ABSTRACT

Fossil fuels are the most imperative parameters to flourish the every sphere of modern civilization including industrial development, transportation, power generation and easing the accomplishment of works. The rapid increase in usage of fossil fuel has unavoidable deleterious effect on environment. The international consciousness for environment protection is growing and ever more strict emission legislations are being enacted. Simultaneously the storage of fossil fuel is depleting. Hence, the above situations promote the scientists to find alternative sustainable fuels along with their suitable using technique which will reduce the pollutant emission and will be applicable for gaining satisfactory engine performance. In these perspectives, alcohol fumigation is getting high demand as an effective measure to reduce pollutant emission from diesel engine vehicles. Alcohol fumigation is a dual fuel engine operation technique in which alcohol fuels are premixed with intake air. The aim of this paper is to identify the potential use of alcohols in fumigation mode on diesel engine. In this literature review, the effect of ethanol and methanol fumigation on engine performance and emission of diesel engine has been critically analyzed. A variety of fumigation ratios from 5% to 40% have been applied in different types of engines with various types of operational mode. It has been found that the application of alcohol fumigation technique leads to a significant reduction in the more environment concerning emissions of carbon dioxide (CO_2) up to 7.2%, oxides of nitrogen (NO_x) up to 20% and particulate matter (PM) up to 57%. However, increase in carbon monoxide (CO) and hydrocarbon (HC) emission have been found after use of alcohol fumigation. Alcohol fumigation also increases the BSFC due to having higher heat of vaporization. Brake thermal efficiency decreases at low engine load and increases at higher engine load.

Contents

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1. Introduction

Nowadays, the global transportation sector completely relies on diesel engine vehicles for public and commercial transportation from the point of view of better efficiency and durability. However, this transportation sector is responsible for 26% of greenhouse gas emission and global warming is the corollary of the greenhouse gas [1]. Simultaneously diesel engine vehicles are the dominant sources of respirable suspended particles in air [2,3]. Primary particulate matter (PM) from diesel vehicles consists of various types of chemical components such as elemental carbon, organic carbon, inorganic ions, trace elements etc. [4–6]. These particles have extremely harmful effects on human health and environment. Numerous studies have proved that these particles cause respiratory and cardiovascular health problems [7–10] and neurodegenerative disorders [11,12]. In urban cities, vehicular sources are responsible for around 70–75% NO_x emission. NO_x is one of the major cause of smog, ground level ozone and also a cause of acid rain [13,14]. Thus, international consciousness for environment protection is growing to reduce such emission from diesel engine vehicles [15]. To achieve that emission standard many engine manufacturing communities already have devoted significant resources to reduce emission from diesel-powered engines. In this regard, the use of alternative and sustainable biofuels such as biogas, bio alcohol and biodiesel are being considered as effective step to reduce the greenhouse gas, PM and NO_x emission from diesel engines [16–21]. In a recent study, International Energy Agency reported that biofuels could be a key alternative fuel technology to reduce the greenhouse gas from diesel-powered engines [22].

Moreover, the sources of fossil fuel are dwindling day by day. According to an estimate, the fossil fuel reserves will continue until 41 years for oil, 63 years for natural gas and 218 years for coal [23–25]. The increasing industrialization and motorization of the world has led to dearth situation in the field of energy supply. Again the price of petroleum oil is becoming higher on daily basis. These pose a challenge to availability of fossil fuel. At these circumstances, demand of alternative biofuels is increasing as a substitute of fossil fuel in transportation sector for energy security issues.

Among the biofuels such as biogas, bioalcohol and biodiesel, alcohol seems to be the most attractive and promising alternative fuels due to its storage facility, availability and handling. High pressure is required to use biogas for automobile. Again leakage from biogas may cause problem. Biodiesel from edible vegetable oil may cause the dearth situation to supply of food for population. The use of non-edible oil as biodiesel sources requires a large-scale cultivation that may cause decrease in food crops.

Alcohol fuels can be used with diesel fuel in different duel fuel operation techniques. The most used methods are blending and fumigation. In blending method, alcohol fuels are mixed with diesel fuel before injecting inside the cylinder. To stabilize the miscibility of blending alcohol with diesel fuel extra additives are required. Hence there is a limitation on amount of alcohol which can be used for blending operation. Alcohol fumigation has been defined simply as the introduction of alcohol fuel into the intake air upstream of the manifold either by spraying, carbureting or injecting. This method of introduction has the advantage of providing a portion of the total fuel supply premixed with the intake air thus improving air utilization. This method requires minor modification of engine which is done by adding low pressure fuel injector, separate fuel tank, lines and controls [26,27] but allows a large percentage of alcohol fuels to be used in engine operation since no additives are required for stabilizing the miscibility of alcohol and diesel fuel [27,28]. As a result, the efficiency of engine will be better in fumigation mode.

In this literature review, a wide range of diesel engine sizes and types was investigated at different operation conditions. 4-cylinder naturally aspirated direct ignition diesel engine was most frequently used. Different percentages of fumigation were applied to get the optimize result. Engine efficiency and emission characteristics are discussed at different sections to get the clear scenario of the effect of alcohol fumigation on engine efficiency and emission.

The main purpose of the present study is to provide a comprehensive review of the literature related to the potential use of alcohol fumigation on diesel engine.

2. Alcohol as a supplementary fuel in diesel engine

The use of alcohol fuels in internal combustion engine is not new. These fuels have been used intermittently in internal combustion engine since their invention. The first commercial use of ethanol as fuel started when the automobile company Ford designed Henry Ford's Model T to use corn alcohol, called ethanol

in 1908. Ethanol became established as an alternative fuel in 1970s due to oil crisis [26]. However, fossil fuel has been the predominant transportation fuel since the invention period of automotive engines due to the ease of operation for engine and availability of supply. But compared to alcohol fuels, fossil fuels have some disadvantages as an automotive fuel. Petroleum fuel has lower octane number and emits much more toxic emission than alcohol fuels. Due to having much more physical and chemical divers than alcohol, complex refining processes are required to ensure the consistent production of diesel and gasoline from petroleum fuel [29]. Moreover in recent years concern about environmental pollution has been increased. Therefore, alcohol fuels are attracting attention worldwide as supplementary fuel.

2.1. Renewable sources of alcohol

Alcohol is a form of renewable energy which can be produced from carbon based agriculture feedstocks, local grown crops and even waste products including waste paper, tree trimmings and grass [30]. Sugarcane residue is another renewable energy source of alcohol production [31]. In recent years, an increasing trend of alcohol fuel production from renewable sources has been found globally. Table 1 clearly shows increasing trend of ethanol fuel production throughout the world.

2.2. Alcohol fuel ethanol

Ethanol consists of carbon, hydrogen and oxygen. Ethanol contains 2-carbon atoms having the molecular formula CH_3CH_2OH and isometric with di-methyl-ether (DME). Ethanol is capable to mix with water completely. ethanol has strong corrosion effects on aluminum, brass and copper made mechanical components. Ethanol also reacts with rubber and causes clogging inside fuel pipe. To avoid this problem, it is recommended to use fluorocarbon rubber instead of rubber [40]. However, due to higher compression ratio, ethanol allows more engine power than gasoline fuel. Ethanol is safer for transportation and storage for its higher auto-ignition temperature than that of diesel fuel [41,42]. By fermentation and distillation process, ethanol can be produced from starch crops after converting into simple sugars. Ethanol can be produced from a variety of cellulosic feedstocks such as rice straw, corn stalks, sugarcane bagasse, switchgrass and pulpwood. Ethanol from waste wood has significant potentiality to reduce CO_2 emission from the life-cycle greenhouse gas [43,44].

2.3. Alcohol fuel methanol

Methanol (CH_3OH), the most simple of the alcohols, is a light, colorless, volatile, flammable liquid with a distinctive odor [45]. Methanol does not contain sulfur or complex organic compounds. Methanol gives higher thermal efficiency and emits less amount of pollutant emission than petroleum fuels. Due to having higher octane number, methanol is superb fuel for engines having high compression ratio. As an alcohol fuel, potential resources of methanol are huge. It can be made from any organic source including biomass. Although, most of methanol is produced from coal and natural gas, recently a number of studies have been done to evaluate the feasibility of bio methanol production from renewable and sustainable sources. In this regard, forest biomass has obtained considerable attention to be an environmentally friendly sustainable source of methanol production [46,47]. However, methanol has lower calorific value and density than petroleum fuel hence larger storage tank is required to be installed in vehicles.

Table 1
Summary of ethanol fuel production annually (millions of U.S. liquid gallons per year) from 2007 to 2011 by top producer countries [32–39].

Country or region	2007	2008	2009	2010	2011
United States	6485	9235	10,938	13,231	13,900
Brazil	5019.2	6472.2	6577.89	6921.54	5573.24
European Union	570.30	733.60	1039.52	1176.88	1199.31
China	486.00	501.90	541.55	541.55	554.76
Canada	211.30	237.70	290.59	356.63	462.3
Thailand	79.20	89.80	435.20	270.13	289.29
India	52.80	66.00	91.67	110	135
Colombia	74.90	79.30	83.21	73.96	79.26
Australia	26.40	26.40	56.80	66.04	87.2

U.S liquid gallon≈3.79 L.

2.4. Physicochemical properties of alcohols as fuel

Alcohol fuels such as ethanol and methanol are viable alternative fuels for compression ignition (CI) engines [48,49]. Alcohol has some effective characteristics which support complete combustion process and reduce pollutant emission from diesel engine. The characteristics are

1. Alcohol has low viscosity than diesel fuel which makes the alcohol easily to be injected and atomized and mixed with air.
2. Due to having high oxygen content, high stoichiometric air–fuel ratio, high hydrogen–carbon ratio and low sulfur content, alcohol emits less emission.
3. Since alcohol has higher heat of vaporization, which results in cooling effect in the intake process and compression stroke. As a result the volumetric efficiency of the engine is increased and the required amount of the work input is reduced in the compression stroke.
4. Alcohol has high laminar flame propagation speed, which may complete the combustion process earlier. This improves engine thermal efficiency [50,51].

Alcohol fuels such as ethanol and methanol have the same physical properties as that of petroleum fuels. The physical properties of alcohol fuels in comparison to gasoline and diesel fuels are given in Table 2.

Alcohol is promising alternative transportation fuel because of its properties which allow its utilization in existing diesel engine with minor hardware modifications. Alcohols have high octane ratings. Therefore, higher compression ratios can be achieved before engine starts knocking which ensures more power supply efficiently and economically from engine. Alcohol burns clearly than regular petroleum fuel hence emits less amount of carbon monoxide (CO), unburned hydrocarbon (HC) and oxides of nitrogen [56–58]. Alcohol from biomass reduces 7% CO_2 emission than reformulated gasoline [26]. Alcohol has high latent heats of evaporation, leading to reduction in the peak in-cylinder temperature during combustion process hence NO_x emission decreases [59,60].

Alcohols are attracting the attention throughout the world due to its renewable sources, cheaper cost of production and environmentally friendly fuel characteristics. Alcohol can be produced locally and production processes are simple and eco-friendly. The use of alcohol as a substitute renewable fuel in compression engine is an effective step to reduce the toxic emission. The corrosion effect on various engine parts due to alcohol fuels can be solved by transesterification process. Although the use of alcohol fuels is still small compared to diesel fuel, the scenario is changing rapidly. Plenty of renewable-resources, new cost reducing technologies, ongoing consciousness on

Table 2
Comparison of various properties of primary alcohol fuels with natural gas, ester, gasoline and diesel [52–55].

	Methane	Methanol	Dimethyl ether	Ethanol	Gasoline	Diesel
Formula	CH_4	CH_3OH	CH_3OCH_3	CH_3CH_2OH	C_7H_{16}	$C_{14}H_{30}$
Molecular weight (g/mol)	16.04	32.04	46.07	46.07	100.2	198.4
Density (g/cm^3)	0.00072[a]	0.792	0.661[b]	0.785	0.737	0.856
Normal boiling point (°C)	−162	64	−24.9	78	38–204	125–400
LHV (kJ/cm^3)	0.0346[a]	15.82	18.92	21.09	32.05	35.66
LHV (kJ/g)	47.79	19.99	28.62	26.87	43.47	41.66
Exergy (MJ/l)	0.037	17.8	20.63	23.1	32.84	33.32
Exergy (MJ/kg)	51.76	22.36	30.75	29.4	47.46	46.94
Carbon content (wt%)	74	37.5	52.2	52.2	85.5	87
Sulfur content (ppm)	7–25	0	0	0	200	250

[a] Values per cm^3 of vapor at standard temperature and pressure.
[b] Density at $P=1$ atm and $T=-25$ °C.

environment pollution and scarcity of energy supply are slowly but surely accelerating the markets of alcohol fuels.Tables 3 and 4

3. Fumigation method as a dual fuel operation in CI engine

Several techniques are available involving alcohol–diesel dual-fuel operation in CI engine. The most common methods applied for achieving dual fuel operation are:

1. Alcohol fumigation – in this mode, alcohol fuel is introduced into the intake air upstream of the manifold by spraying or carbureting [61–66].
2. Alcohol–diesel blend – in this mode, alcohol and diesel fuels are premixed uniformly and then injected into cylinder directly through the fuel injector [67–72].
3. Alcohol–diesel emulsification – in this mode, an emulsifier is used to mix the fuels to prevent separation [73–76].
4. Dual injection – in this mode separate injection systems are used for fuels injection [77,78].

However, the alcohol–diesel blend and alcohol fumigation modes are mostly used to apply alcohol and diesel fuels together in CI engine when other modes are investigated at some amount [79,80]. In the blend mode, alcohol and diesel fuels are premixed before injecting through the fuel injector into the cylinder. In this system large amount of alcohol supply is limited due to having poor miscibility of alcohol with diesel. The blends are not stable and may be separated in the presence of water. To improve the miscibility and to overcome two fluid phase separation problem extra additives are used in alcohol–diesel blending which reduces the supply of the energy to engine [81,82]. As a result, blending mode can supply less amount of alcohol on an energy basis (25%) than fumigation mode (50%) [83]. Again, the addition of alcohol into diesel fuel, changes the physical properties of diesel fuel. The addition of alcohol as a blend with diesel fuel decreases the viscosity of diesel fuel, affects the cetane number to drop and reduces the heating value. In fumigation mode, alcohol is premixed with intake air stream by vaporizing or injecting. Fig. 1 shows the schematic diagram of alcohol fumigation system.

This requires additional carburetor, vaporizer or injector, along with a separate fuel tank line and controls [84]. This separate fuel tank gives opportunity to engine operation to be reverted to neat diesel operation if any problem is encountered with alcohol combustion [83]. In fumigation approach, alcohol is vaporized then mixed with intake air which lowers the intake mixture temperature and increases its density. Thus, large amount of air can be delivered and greater amounts of power can be achieved if right portion of fuel is added [84]. Since alcohol is premixed with intake air so there is no necessity to add any additives in alcohol fumigation approach to improve the miscibility of alcohol and diesel fuel. Due to this benefit fumigation can replace up to 50% diesel with alcohol [83]. From the above, it is clear that although fumigation mode increases weight in vehicles body but this system is able to supply more energy to engine than blending mode. Since more energy makes the possibility of the availability of more power so fumigation mode is being considered as a viable solution of alternative diesel fuels.

4. Engine performances

4.1. Brake-specific fuel consumption (BSFC)

4.1.1. Effect of alcohol fumigation on BSFC

Brake-specific fuel consumption (BSFC) is the ratio between mass fuel consumption and brake effective power and it is inversely proportional to thermal efficiency for a given fuel. BSFC is computed by following equation:

$$BSFC = \frac{(q_{m,d} + q_{m,a})}{P_b}$$

where P_b is the brake power in kW, $q_{m,d}$ and $q_{m,a}$ are the mass consumption rates of diesel fuel and alcohol, respectively, in g/h. Diesel engine operated in fumigation mode, consumes more fuel to maintain same thermal efficiency compared to diesel fuel. Alcohol has higher heat of evaporation compared to diesel fuel. Thus, less amount of heat is extracted during combustion process that must be compensated with higher fuel consumption.

Engine performance of a modified CI engine using diesel as baseline fuel and vaporized ethanol as a supplementary fuel was investigated by Ajav et al. [85]. In this experiment engine was operated at two conditions where in the first mode, air was at 20 °C ambient temperature and in the second mode; air was preheated at 50 °C before injection. Authors reported there is no significant change in BSFC whether vaporized ethanol was preheated or not but BSFC decreased with increasing load. This happens because of brake power increases with increasing load.

Janousek [86] investigated engine efficiency of a 4-cylinder diesel engine using atomization technique with ethanol fumigation. They conducted the study at different engine speeds from 1000 to 2400 rpm with 200 rpm interval. According to their results, alcohol fumigation leads to increase in BSFC with increasing engine speed and decreasing engine load compared to diesel fuel. They measured maximum BSFC of 285 g/kWh at engine speed 2400 rpm with 50% full engine load.

A number of authors [87–89] experimentally analyzed the effect of alcohol fumigation on engine performance following same procedures. They conducted their experiment with five engine loads and corresponding five mean effective pressures in

Table 3
Studies of various researchers on engine performance applying alcohol fumigation.

Used alcohol	Ref. fuel	Engine tested	Operation conditions	Test results	References
Vaporized ethanol at 20 °C and 50 °C	Pure diesel	1-cylinder, NA, WC, DI	1500 rpm	BSFC no significant changes and BTE increases up to certain level then decreases	[85]
Industrial grade ethanol and methanol	Pure diesel	4-cylinder, TC	1800 rpm	BSFC and BTE increased	[97]
Ethanol	Pure diesel	1-cylinder, WC	1500 rpm	BSFC increased and BTE increases with fumigation temperature	[98]
Ethanol	Pure diesel	1-cylinder	1500 rpm, 1720 rpm, 2000 rpm	BSFC increased and BTE increases with substitution of ethanol	[99]
Ethanol	Pure diesel	1-cylinder,NA, EGR	1500 rpm	BTE increased	[96]
Ethanol	Pure diesel	Multi-cylinder, TC	Half load and 2000 rpm and 2400 rpm	BTE increased	[100]

WC—Water cooled, NA—natural aspirates, DI—direct injection, TC—turbocharged, EGR—exhaust gas recirculation.

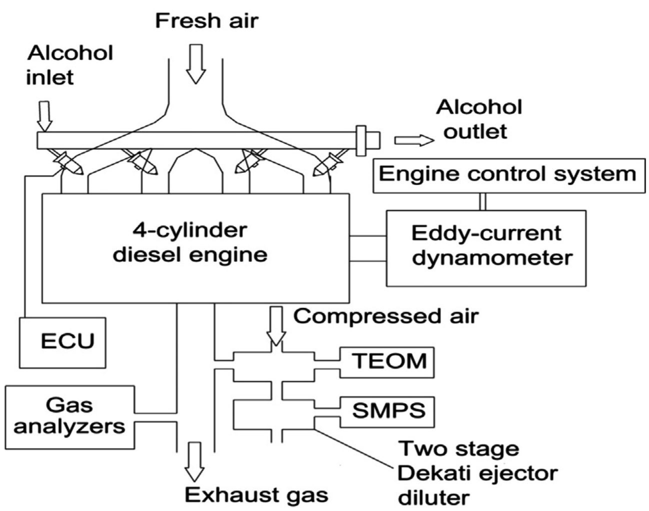

Fig. 1. Schematic of experimental setup of alcohol fumigation system. (reprinted with permission from Elsevier, License number: 3151120464936).

a 4-cylinder naturally aspirated direct injection diesel engine. Tsang et al. [87] experimentally analyzed the effect of 5%, 10%, 15% and 20% ethanol fumigation on engine performance. Their results showed that BSFC was higher than that of Euro V diesel fuel for any percentage of fumigation fuel and increased with the level of fumigation. They measured 250.5 g/kWh and 255.8 g/kWh BSFC at 0.70 MPa for 10% and 20% fumigation ethanol, which are 7% and 9% higher than operating on Euro V diesel fuel. Such an experimental work was also carried out by Cheng et al. [88] using biodiesel with 10% fumigation methanol operating the engine at a constant speed of 1800 rev/min. They observed that BSFC increased at fumigation mode compared to ultralow sulfur diesel fuel. However, BSFC decreased with increasing engine load. They found minimum value of BSFC 254.9 g/kWh for fumigation mode whereas BSFC was 226.1 g/kWh for ultralow sulfur diesel fuel at the engine load of 0.56 MPa. Zhang et al. [89] analyzed the effect of alcohol fumigation on brake specific fuel consumption. They conducted the experiment operating the engine at the maximum torque engine speed of 1800 rev/min. They observed that fuel consumption rate increased with fumigation level due to lower calorific value compared with diesel fuel. Methanol fumigation leads to higher fuel consumption than ethanol fumigation since methanol has lower calorific value than ethanol.

Cheung et al. [90] analyzed the effect of methanol fumigation on BSFC. In this experiment, methanol was fumigated with biodiesel then results were compared with diesel fuel. They carried out the experiment at a constant speed of 1800 rev/min for three engine loads and their corresponding brake mean effective pressures (BMEP). They observed that BSFC increased with increasing level of fumigation due to lower calorific value of methanol.

4.1.2. Summary

From the above literatures review, it is clear that BSFC increased after using alcohol fumigation compared to neat diesel fuel. The lower calorific value of alcohol may be attributed to the reason behind the increase of BSFC for alcohol fumigation. Because, due to cooling effect, more amount of fuel is needed to support the complete combustion and to provide the required amount of power.

4.2. Brake thermal efficiency (BTE)

4.2.1. Effect of alcohol fumigation on BTE

Thermal efficiency is defined as the brake power divided by the fuel energy supplied through fuel injection. Thermal efficiency is calculated by the following formula:

$$BTE = \{P_b/[(q_{m,d} \times Q_{LHV,d}) + (q_{m,a} \times Q_{LHV,a})]\} \times 100\%$$

where P_b is the brake power, kW; $q_{m,d}$ is the mass consumption rate of diesel fuel, kg/s; $q_{m,a}$ is the mass consumption rate of methanol, kg/s; $Q_{LHV,d}$ is the lower heating value of diesel fuel, kJ/kg; $Q_{LHV,a}$ is the lower heating value of methanol, kJ/kg. In this work, literatures illustrated the effect of alcohol fumigation on the BTE have been surveyed. Most authors have reported around same results after investigating alcohol fumigation method on diesel engine.

Zhang et al. [91] experimentally investigated the effect of methanol fumigation on break thermal efficiency of a four cylinders in line DI engine at fixed speed 1920 rev/min with 10%, 20% and 30% fumigation methanol with diesel fuel. They conducted the test operating at five different loads and their corresponding brake mean effective pressures. They observed decrease in BTE at low loads and they measured 10% and 11% BTE drops at 0.13 MPa and 0.27 MPa, respectively, for 30% of fumigation methanol. No significant change was found in BTE at medium and high engine loads.

Abu-Qudais et al. [79] studied and compared the effect of ethanol fumigation and ethanol–diesel fuel blends on BTE of a single cylinder DI diesel engine at various engine speeds. The results showed ethanol fumigation increased the BTE than ethanol blends but fumigation and blends methods have the same characteristics in case of affecting BTE. When ethanol was added to diesel following two methods, the BTE increased to a certain

engine speed then again decreased with increasing engine speed. In case of fumigation, the maximum increase of BTE was measured 7.5% at 1500 rpm for 20% ethanol fumigation. Tsang et al. [87] also reported that ethanol fumigation gave a positive BTE change only at higher engine load. At lower engine load condition, BTE decreased at any level of fumigation except at the engine load of 0.70 MPa with 20% fumigation ethanol.

Cheng et al. [92] experimentally analyzed thermal efficiency using 10%, 20% and 30% of fumigation methanol. They conducted the experiment operating the engine at a constant speed of 1800 rev/min with five different loads and their five corresponding brake mean effective pressures. They reported that methanol fumigation gives lower BTE at lower load and higher BTE at higher engine load compared to diesel fuel. BTE decreased with increasing the level of fumigation at low load condition and that was up to about 13%. Reduction of BTE with fumigation level was not significant at medium and high load conditions. Cheng et al. [88] also investigated the effect of methanol fumigation with biodiesel on thermal efficiency using same engine setup and operating conditions. They observed higher BTE at each engine load compared to ultralow sulfur diesel and maximum BTE 39.6% was obtained with 10% fumigation methanol.

Zhang et al. [93] investigated the BTE in an in-line 4-cylinder diesel engine using 10%, 20% and 30% of methanol fumigation where euro V diesel fuel having 10-ppm weight of sulfur was standard fuel. They performed experiment at constant engine speed of 1800 rev/min with five different engine loads. They reported that at low engine load condition, BTE decreased with increasing the percentage of fumigation methanol but increased with engine load. BTE drops were measured 11.2% for 0.008 MPa, 6.4% for 0.19 MPa and 5.35% for 0.38 MPa engine load. At high engine load conditions of 0.58 MPa and 0.7 MPa the increase was about 2% with different level of fumigation.

In another experiment using 10% and 20% methanol and ethanol fumigation, Zhang et al. [89] found that methanol and ethanol fumigation both reduces BTE at low engine load and increases BTE at high engine load compared to diesel fuel. They measured BTE decrease 2–5% for 0.08 MPa and 3–8% for 0.39 MPa engine loads. At 0.70 MPa, BTE increased 10% and 9% with 10% and 20% fumigation methanol. In case of ethanol they measured 2–4% and 7% decrease at the engine loads of 0.08–0.39 for 10% and 20% fumigation and at 0.7 MPa the increase was 3% for 20% fumigation.

Heisey et al. [94] conducted a test in a single cylinder DI diesel engine by fumigating methanol. They reported that 200 proof (100% (v/v) EtOH) ethanol leads to an increase in BTE with increasing engine load. Others proof of ethanol such as 180 proof (90% (v/v) EtOH), 160 proof (80% (v/v) EtOH) and 140 proof (70% (v/v) EtOH) show same behavior like 200 proof ethanol. However, maximum increase in BTE has been found at full load condition for 200 proof ethanol compared to other proof of ethanol.

Cheung et al. [90] investigated the methanol fumigation with biodiesel when biodiesel was the baseline fuel. They reported that at low load condition BTE decreased with increasing fumigation level. They measured that at low engine load of 0.19 MPa, when the fumigation ratio increases from zero to 0.55, BTE drops from 27% to 23.2%. At 0.38 MPa, BTE increases slightly at lower level of fumigation but after fumigation ratios becoming higher than 0.26, BTE decreases up to a magnitude of 2% whereas 1% variation in magnitude has been found at 0.56 MPa with all levels of fumigation ratio. They also mentioned that no reduction was found in BTE when the fumigation ratio lies within 0.2 or at higher engine loads condition.

Houser et al. [95] conducted tests on an Oldsmobile 5.7l V-8 Diesel engine fumigated with methanol when methanol provides up to 40% of fuel energy. For the low and medium load (1/4 and 1/2 of full load settings), thermal efficiency generally dropped off with increasing methanol fumigation. However, for the higher and full load (3/4 and full load settings), an increasing trend was observed for all engine speeds.

In same engine condition, Hebbar et al. [96] compared the thermal efficiency using EGR with alcohol fumigation and without fumigation. They reported that thermal efficiency drops off at both hot EGR with and without fumigation compared to diesel fuel but reduction was less for ethanol fumigation with EGR. They measured that the loss of efficiency was around 20% for ethanol fumigation. Without fumigation, the loss was up to 40%. A marginal loss of around 5% was measured for 30% EGR and up to 10% ethanol fumigation after that BTE increased around 20% as the level of fumigation increased.

4.2.2. Summary

Based on the literatures review above, it is clear that alcohol fumigation in a diesel engine affects the brake thermal efficiency in two ways. Alcohol fumigation decreases the BTE at lower engine load condition and increases the BTE at medium and higher engine load condition. The reduction of BTE at lower engine load condition can be explained by attributing the following points:

(1) At low engine loads, the excess air ratio is very high hence the intake air and the fumigation alcohol form a mixture which might be too lean to support combustion, resulting in deterioration of combustion efficiency and thus reduced the BTE.
(2) Alcohol has much higher heat of vaporization (1178 kJ/kg) compared with that of biodiesel (250 kJ/kg). Due to this characteristic alcohol might cool down the combustible mixture hence there will be a drop in BTE.

The increase of BTE at medium and higher engine loads can be explained by attributing the following reasons:

(1) Homogeneous air/alcohol mixture burns faster hence provides more premixed combustion which tends to increase the BTE.
(2) Alcohol has lower cetane number which increases the ignition delay hence energy is released within a very short time, resulting reduction in the heat loss from the engine as there is no sufficient time for transferring heat through the cylinder wall to the coolant.

5. Emission

5.1. Oxides of nitrogen (NO_x)

5.1.1. Effect of alcohol fumigation on NO_x emission

NO*x* is a grouped emission composed of nitric oxide (NO) and nitrogen dioxide (NO_2). NO*x* is the most detrimental gaseous emission from diesel engine. NO is the majority of NO_x emissions inside the engine cylinder [101]. NO_x formation is complex chemically and physically. NO_x formation highly depends on the in-cylinder temperature and other engine operating conditions also effect the formation of NO_x such as injection timing, load, engine speed and fuel to Air (F/A) ratio [102]. Three mechanisms are involved in the formation of NO_x: thermal, prompt and nitrous oxide, also named N_2O-intermediate mechanism [103]. According to thermal mechanism, reaction between N_2 and O_2 occurs at high temperatures inside combustion chamber through a series of chemical steps known as the Zeldovich mechanism. NO_x formation occurs at temperatures above 1500 °C, and the rate of formation increases rapidly with increasing temperature [104–106]. According to prompt mechanism, fuel bound nitrogen is one of the significant parameter for formation of prompt NO_x [102]. The formation of prompt NO_x is led by the intermediate hydrocarbon fragments from fuel combustion – particularly CH and CH_2 –

Table 4
Studies of various researchers on engine emission applying alcohol fumigation.

Used alcohol	Ref. fuel	Engine tested	Operation conditions	Test results	References
Methanol	Ultralow sulfur diesel	4-cylinder,NA,WC,DI In line diesel engine	Three different loads and 1800 rpm	NO_x, CO_2 and PM decreased CO and HC increased	[90]
Ethanol and methanol	Pure diesel	1-cylinder,NA, DI, 4-stroke engine	Full load and 3000 rpm	NO_x reduced, CO increased	[94]
Methanol	Diesel	4-cylinder, DI	Three different loads and 1500–2000 rpm	NO_x decreased	[95]
Ethanol	Pure diesel	6-cylinder, TC,DI, 4-stroke	Different loads and 2500 rpm	NO_x reduced and CO increased	[61]
Ethanol and methanol	Pure diesel	4-cylinder,TC, 4-stroke	25%,50%,75% and full load, 1500 rpm and 2100 rpm	NO_x increased, CO and HC decreased.	[118]
Ethanol and methanol	Pure diesel	6-cylinder, TC	1500 rpm-300 rpm	HC unchanged and PM reduced	[119]
Ethanol	Pure diesel	Multi-cylinder, TC	Half load and 2000 rpm and 2400 rpm	CO and HC reduced	[100]

WC—Water cooled, NA—Natural aspirates, DI—Direct injection, TC—Turbocharged, EGR—Exhaust gas recirculation.

reacting with N_2 in the combustion chamber and the resulting C–N containing species then proceed through reaction pathways involving O_2 to produce NO_x [104].

The N_2O-intermediate mechanism is as follows:

$$N_2+O+M=N_2O+M$$

$$H+N_2O=NO+NH$$

$$O+N_2O=NO+NO$$

“M” is a “third-body collision partner”. The N_2O-intermediate mechanism is significant at low combustion or cylinder temperatures [103]. In this work, a wide range of variation in results has been found from different authors. Some authors reported that NO_x emission decreases with alcohol fumigation as alcohol has the cooling effect on combustion temperature compared to diesel fuel. Simultaneously some authors also reported that NO_x emission increases due to having higher amount of oxygen in alcohol fuel. Literature reviews are mentioned below.

Zhang et al. [91] investigated the effect of 10%, 20% and 30% fumigation methanol on NO_x emission of a four cylinders in line DI engine at the engine speed 1920 rev/min. They found that all level of fumigation gives lower NO_x emission than diesel fuel. However, NO_x emission increases with level of fumigation but decreases with increasing engine loads. They measured reduction in NO_x about 11.6% for 0.13 MPa, 20% for 0.27 MPa, 20.8% for 0.4 MPa and 13.4% for for 0.53 MPa engine load for 30% fumigation. No significant change was found at higher engine load.

Engine emission of a modified CI engine at various loads using vaporized ethanol as a supplementary fuel was investigated by Ajav et al. [85]. Results showed that NO_x emission increased 0.4% in case of ethanol vaporization (unheated) and 0.7% decreased in case of ethanol preheating compared with diesel fuel. They explained the effect of ethanol heating by attributing that the displacement more diesels with the help of preheating less air–fuel ratio was obtained that caused lower in NO_x emission.

Methanol increases ignition delay hence large amount of fuel can be combusted in the premixed mode [107,108] which increases the combustion temperature. Attributing this reason, many authors [88,92] reported that NO_x emission increases with increase of engine loads. Cheng et al. [92] observed that methanol fumigation reduces NO_x emission compared to baseline diesel fuel. However, NO_x emission increases with increasing engine load. They measured average reduction about 6%, 9% and 11%, respectively, for 10%, 20% and 30% fumigation methanol. The maximum reduction was found 20% at medium load (0.4–0.5 MPa) for 30% fumigation methanol. Cheng et al. [88] also reported 6.2% and 8.2% decrease in NO_x emission using biodiesel with 10% fumigation ethanol compared to ultralow sulfur diesel fuel and NO_x emission decreased with increasing engine load when they used same engine and experimental setup.

Zhang et al. [93] also reported reduction in NO_x emission for 10%, 20% and 30% methanol fumigation with Euro V diesel fuel and the effect of further addition of Diesel Oxidation Catalyst (DOC) in fumigated fuel. They found that NO_x emission decreased compared to Euro V diesel fuel with increasing fumigation concentration. The maximum reduction of NO_x emission was obtained at 0.39 MPa for 30% fumigation methanol. In case of using DOC, no significant reduction was found. In another experiment, Zhang et al. [89] also analyzed the effect of ethanol fumigation on NO_x emission. They observed that ethanol fumigation increased NO_x emission compared to methanol. Since ethanol has lower latent heat of vaporization than methanol, there is an increase in combustion temperature which increases NO_x emission.

Heisey et al. [94] reported that 200 proof (100% (v/v) MeOH) methanol and 200 proof (100% (v/v) EtOH) ethanol have approximately same effect on NO_x emission. Wet methanol (160 proof) produces a significant reduction in NO_x formation, especially when the amount of fumigated alcohol exceeds 15%.

Chauhan et al. [84] experimentally investigated the NO_x emission for ethanol fumigation. They observed that at overall engine load conditions, NO_x decreased up to a certain level of fumigation then again increased. At 20% load, NO_x emission is minimum on 22% fumigation of ethanol but at 45% load, NO_x emission decreases up to 20% of ethanol substitution then starts increasing. At 70% load and at full load, NO_x emission decreases up to 16% ethanol fumigation then starts increasing.

Houser et al. [95] conducted tests on an Oldsmobile 5.7l V-8 Diesel engine fumigated with methanol when methanol provides up to 40% of fuel energy. Emission of NO was observed to decrease for all rack settings and speeds as the amount of methanol fumigated was increased. For the lower load condition (1/4 and 1/2 of full load setting), it appears as though there is a threshold value in the vicinity of 5–10% methanol addition above which the reduction of NO becomes insignificant. For the higher load settings, this trend does not seem to exist. Also, there does not seem to be any consistent speed effect displayed throughout the data.

Hayes et al. [109] conducted a test in a turbocharged diesel engine with different proofs of alcohol fumigation at different engine loads. At a load of 0.8 MPa, NO_x emission is greater than diesel fuel for higher level of fumigation but NO_x decreased within 150 proofs (75% (v/v) EtOH) of ethanol fumigation. At 0.5 MPa, NO_x emission decreased with level of fumigation.

5.1.2. Summary

In the above literatures review, variation in results have been found since some authors reported that alcohol fumigation

decreased NO_x emission compared to that of neat diesel fuel and some authors reported increase in NO_x emission. Depending on engine load, NO_x emission is higher at low engine load than medium and higher engine load. However, all authors mentioned that the formation of NO_x in a diesel engine strongly depends on the combustion temperature and along with the concentration of oxygen present in the combustion process. The positive effect of alcohol fumigation on NO_x emission can be explained by attributing the following conclusions:

(1) Alcohol has high latent heat of vaporization hence less amount of heat is released during combustion process which reduces the combustion temperature, leading to the reduction of NO_x formation especially under the lean conditions at lower engine loads.
(2) At high engine load, there is a reduction in the air/fuel ratio in the fumigation mode hence diesel fuel is burnt with such an air and alcohol mixture that might have a negative effect on the oxygen available for NO_x formation, resulting reduction in NO_x emission.

In some cases, NO_x emission increases with increasing level of fumigation. The following reasons can be attributed for increase in NO_x emission:

(1) Alcohol contains higher oxygen than diesel fuel hence application of alcohol increases oxygen supply which might increase the NO_x emission.
(2) The poor auto-ignition properties of fumigated alcohol leads to an increase of fuel burned in the premixed mode which increase the combustion temperature and hence increase the NO_x emission.

5.2. Carbon monoxide (CO_2)

5.2.1. Effect of alcohol fumigation on CO_2 emission

CO is another harmful gaseous emission from diesel engine. Formation of CO is the result of in-complete combustion. If the in-cylinder temperature during combustion process is not sufficient to support the complete combustion then transformation of CO to CO_2 is not occurred. Results from different literatures show that alcohol fumigation has negative effect on CO emission.

The increase of CO emission with level of fumigation methanol was reported by Zhang et al. [91]. They tested four cylinders in line DI engine at the engine speed 1920 rev/min with five different engine conditions which has been mentioned in BTE section. According to their investigation, brake specific CO emission increased with increasing engine load and with level of fumigation methanol compared to diesel fuel. They found that BSCO emission increases from 7.8 g/kWh to35.4 g/kWh for 30% fumigation methanol at 0.13 MPa and 1.0 g/kWh to 6.2 g/kWh at 0.63 MPa.

Engine performance of a modified CI engine at various loads using vaporized ethanol as a supplementary fuel was investigated by Ajav et al. [85]. In this experiment engine was run at two conditions where in the first air was unheated at 20 °C ambient temperature and in second air was preheated at 50 °C before injection. They reported that ethanol vaporization increased CO emission because of presence of ethanol in combustion is more like a homogenous charge spark-ignited combustion rather than being droplet-diffusion controlled. Due to displacing higher amount of air by preheating, rich mixtures is formed, leading to higher percentage of CO emission.

Abu-Qudais et al. [79] studied the effect of fumigation and blends method on CO emission of a single cylinder DI diesel engine at various engine speeds. They found that fumigation gives better results than blends. In both cases CO emission increased with increasing ethanol substitution. Regarding engine speeds, CO emission decreased to a certain level of engine speed then again increased with increasing engine speeds. The maximum increase was measured 55% for 20% ethanol fumigation over entire speed range.

The effect of ethanol fumigation on CO emission using a 4-cylinder engine at different engine load conditions was experimentally investigated by Surawski et al. [110]. They operated engine at intermediate engine speed 1700 rpm with four different engine load conditions of 20% (idle), 25%, 50% and 100% of maximum load using 0%, 10%, 20% and 40% fumigation ethanol. Their report showed that CO emission increased at all loads except idle mode. At idle mode, 15% reduction was achieved by using 10% ethanol. CO emission increased significantly in case of 40% fumigation ethanol at all loads.

Tsang et al. [87] also reported the increase in CO emission when they applied ethanol fumigation in diesel engine. They observed that CO emission increases by about 0.6 and 1.3 times with 10% and 20% ethanol fumigation at engine load 0.08 MPa and at engine load 0.70 MPa, the increase was about 1.8 times compared to diesel engine.

The increase of CO emission due to methanol fumigation was also reported by Cheng et al. [92] in a 4-cylinder naturally aspirated direct injection diesel engine. They observed that CO emission increased significantly with increasing level of fumigation methanol. Cheng et al. [88] also reported the increase in CO emission using 10% fumigation methanol with biodiesel in same engine and experimental setup. They found average CO emission increase from 6.14 g/kWh to 12.72 g/kWh compared to ultralow sulfur diesel fuel.

Zhang et al. [93] analyzed the CO emission using two fuel samples of 10%, 20% and 30% fumigation methanol and further addition of diesel oxidation catalysts (DOC). Their results showed that the average CO emission increase was 2.7 times, 3.8 times and 5.5 times of baseline value for three consecutive fumigation ratios. After using DOC, CO emission was reduced by 8–16% at 0.08 MPa and 0.19 MPa engine load. Over 93% reduction was achieved at 0.39 MPa for all concentrations of fumigation methanol. Zhang et al. [89] also investigated the effect of methanol and ethanol fumigation on CO emission using same engine setup and operation conditions. They observed that ethanol reduced CO emission in the same way like methanol but reduced more CO emission than methanol compared to diesel fuel. Their results showed that at 0.08 MPa, CO emissions increased from 13.2 g/kW to 29.2 g/kW for 20% fumigation methanol and in case of 20% fumigation ethanol, CO emission increased from 13.2 g/kW to 28.4 g/kW.

Heisey et al. [94] observed significant increase in CO emissions at low and medium load (1/3 and 2/3 of full load setting) at 2400 rpm. At full load condition, CO emissions show only a slight increase up to the point of 25% alcohol substitution.

Chauhan et al. [84] reported different characteristics of CO emission than other authors using ethanol fumigation at five different loading conditions of 0%, 20%, 45%, 70% and 100% of full load with various percentages of ethanol fumigation. They observed that at each load condition, CO emission decreased from initial level of fumigation to certain level, respectively, then increased with increasing level of fumigation. At 20% and 45% load condition, CO emission reduction is up to 20% of fumigation. At 75% and full load condition, CO emission decreased up to 15% of fumigation then increases with increasing level of fumigation. However, at no load condition, CO emission increases up to 30% of fumigation.

Cheung et al. [90] tested a 4-cylinder naturally aspirated diesel engine operating at a constant speed of 1800 rev/min for three engine loads using methanol fumigation with biodiesel. They reported that CO emission increased at each engine load with increasing fumigation ratio.

Hayes et al. [109] conducted a test in a turbocharged diesel engine with different proofs of alcohol fumigation. The results indicated that the CO emission levels increased greatly as the ethanol flow rate was increased. This was most severe at low loads. Ethanol proof did not have an effect on CO emissions.

5.2.2. Summary

From the above literature review, it is clear that all the authors reported an increase of CO emission with alcohol fumigation compared to neat diesel fuel and. They also reported that CO emission increased with increasing fumigation level but decreased with increasing engine loads. The following reasons can be attributed for the increase of CO emission:

(1) During combustion process, air/alcohol mixture gets trapped in crevices, deposits and quench layer in the engine. Alcohol also tends to lower the in-cylinder gas temperature which might be not able to ignite the trapped alcohol during expansion stroke. Due to this reason CO emission increases remarkably especially at low engine load.
(2) Rapid burning of vaporized alcohol, combustion quenching caused by high latent heats of vaporization and subsequent charge cooling decrease the in-cylinder temperature that might lead to incomplete oxidation of the CO to CO_2 during expansion stroke, resulting an increase in CO emission.

5.3. Hydrocarbon (HC)

5.3.1. Effect of alcohol fumigation on HC emission

Majority of the authors reported an increase in HC emission like CO emission. The reasons behind the formation of HC during combustion are as like as CO formation, alcohol fumigation effects on HC emission in same way as it effects on CO emission.

Zhang et al. [91] investigated the effect of alcohol fumigation on HC emission. They tested four cylinders in line DI engine at the engine speed 1920 rev/min with five steady conditions. From their investigation it has been clear that methanol fumigation increases the HC emission compared to diesel fuel. Moreover, the emission increases with the level of fumigation and decreases with increasing engine loads. Their investigation showed that HC emission increases from 5.4 g/kWh to 52 g/kWh at engine load 0.13 MPa while it varies from 0.8 g/kWh to 2.4 g/kWh for 30% fumigation methanol at 0.63 MPa.

Abu-Qudais et al. [79] analyzed the effect of ethanol fumigation and ethanol–diesel blends on HC emission of a single cylinder DI diesel engine. They conducted the experiment at various engine speeds. Their results showed that due to ethanol addition to diesel fuel, HC emission increased with increasing engine speed in both methods. Increase in fumigation method is lower than blend method. At overall engine speeds the increase in HC emission was measured as 36%.

Surawski et al. [110] measured the increase of HC emission in a 4-cylinder engine using fumigation ethanol at different load conditions. Their result showed that HC emission increased 30% by 20% ethanol substitution at 25% (quarter load) of maximum load. At half load condition, HC emission increased more than double using 40% ethanol substitution.

The increase of HC emission due to ethanol fumigation was also reported by Tsang et al. [87]. They found an increase of about 1.6 and 3.3 times in BSHC with 10% and 20% fumigation at engine load 0.08 MPa compared to Euro V diesel fuel while the corresponding increases at 0.70 MPa are 1.1 and 2.4 times compared to diesel fuel.

Cheng et al. [92] also observed increase in HC emission due to use of 10%, 20% and 30% of methanol fumigation compared to diesel fuel. They found that HC emission increased with level of methanol fumigation but decreased with increasing engine loads. They found maximum increase in HC emission 7 times and maximum reduction in HC emission 3 times.

Zhang et al. [93] analyzed the BSHC emission in a diesel engine. They reported that the increase of BSHC emission with level of fumigation is higher at low engine load and lower at high engine load. They found highest increase in BSHC about 7 times at 0.08 MPa and the maximum reduction was about 3 times at 0.7 MPa compared to diesel fuel. After using DOC, HC emission was reduced by 21–38% at 0.08 MPa and 0.19 MPa engine load. About 90% reduction was achieved at 0.39 MPa for all concentrations of fumigation methanol. In another experiment, Zhang et al. [89] also investigated the BSHC emission characteristics with ethanol and methanol fumigation using same engine setup and operating conditions. They observed that HC emission followed same behaviors as previous. In case of ethanol fumigation, the reduction of HC emission was more than ethanol since ethanol has lower latent heat of vaporization than methanol. HC emission increases from 8.9 g/kWh to 39.5 g/kWh for 20% fumigation methanol and from 8.9 g/kWh to 37.8 g/kWh for 20% fumigation ethanol at 0.08 MPa. At 0.7 MPa, HC emission increases from 0.5 g/kWh to 1.4 and 1.3 g/kWh.

The effect of ethanol fumigation on HC emission was experimentally analyzed by Chauhan et al. [84]. They reported that at 70% and full load, HC emission increased until 11% ethanol substitution then again started to decrease up to 18% ethanol fumigation due to better combustion at higher load.

Hayes et al. [109] conducted a test in a turbocharged diesel engine with different proofs of alcohol fumigation. HC emissions increased greatly compared to diesel fuel. HC emission increased 7.2 times from the diesel levels at low load, 6 times at medium load and 3.8 times at high load.

Schroeder et al. [100] tested a multicylinder, turbocharged diesel engine fumigated with methanol by changing the diesel injection timing. Tests results indicated that advancing the injection timing decreased HC levels in the exhaust gas.

5.3.2. Summary

Based on the above literature review, the following reasons can be attributed to increase the HC emission in alcohol fumigation mode.

(1) In the fumigation mode, quench layer of unburned fumigated alcohol might be formed inside the cylinder. Since alcohol has cooling effect on combustion process, as a result poor combustion temperature might not be able to ignite the unburned fumigated alcohol during expansion stroke which leads to increase in HC emission.
(2) Especially at low engine load condition, due to large amount of excess air, poor fuel distribution and low exhaust temperature, lean fuel–air mixture regions may survive to escape into the exhaust resulting in higher HC emissions.

5.4. Carbon dioxide (CO_2)

5.4.1. Effect of alcohol fumigation on CO_2 emission

Carbon dioxide (CO_2) is the primary greenhouse gas emitted from diesel engine. Formation of CO_2 during combustion process strongly depends on two things: (1) combustion temperature and (2) availability of oxygen. The combustion process consists of two stages, at first stage, carbon monoxide is formed and at second stage, if in-cylinder temperature is sufficient to support the complete combustion and excess oxygen is available then carbon monoxide reacts with additional oxygen to form carbon dioxide. In

this literatures review, most of the authors reported that alcohol fumigation reduced CO_2 emission significantly.

Cheng et al. [88] analyzed the CO_2 emission using biodiesel with fumigated methanol. They reported that CO_2 emission drops to 2.5% compared to diesel.

Zhang et al. [93] investigated the effect of fumigation methanol on brake specific CO_2 emission in diesel engine when 10%, 20% and 30% loads were provided by fumigation methanol. They found that $BSCO_2$ decreases at over all load conditions. At low to medium engine load, the average reduction has been found up to 4.3% for all percentage of fumigation whereas up to 7.2% reduction has been found with 30% fumigation methanol at high engine load.

Chauhan et al. [84] also reported increase in CO_2 after using ethanol fumigation. They reported that at no load condition, CO_2 percentage remains almost constant throughout the level of fumigation but 20% and 45% load condition, CO_2 percentage decreased as ethanol substitution was increased. At full load condition, CO_2 percentage decreased up to 15% of fumigation level then increased. They found 15% ethanol fumigation as optimum level of fumigation.

Cheung et al. [90] also reported reduction in CO_2 emission at three engine load conditions using methanol fumigation with biodiesel at a constant speed of 1800 rev/min. As the fumigation ratio increases from zero to 0.55, CO_2 concentration decreases from 3.47% to 3.21% at 0.19 MPa. When the fumigation ratio increases to 0.6, CO_2 emission decreases from 5.55% to 4.99% at 0.38 MPa. At 0.56 MPa, it decreases from 7.96% to 7.59% as the fumigation ratio increases to 0.4. Pannirselvam et al. [98] also observed lower CO_2 emission using ethanol fumigation compared to base line diesel fuel. They also found that CO_2 emission increased with increasing engine load.

Hebbar et al. [111] experimentally investigated the effect of ethanol fumigation using EGR. Their results showed that CO_2 emission increased with increasing percentage of EGR. They did not find any considerable change at hot EGR with and without fumigation.

5.4.2. Summary

Based on the above literature review, it is clear that there is a significant decrease in CO_2 emission with alcohol fumigation compared to neat diesel fuel. Based on the above literature reviews following conclusions are available:

(1) In fumigation mode, break thermal efficiency decreases which results in a significant increase in fuel consumption, which offsets the potential CO_2 reduction benefits of alcohol.
(2) CO_2 emission greatly depends on the CO emission. In fumigation mode, due to having higher heat of vaporization, alcohol reduces the in-cylinder temperature which leads to incomplete oxidation of the CO to CO_2 during expansion stroke and thus results in an increase in CO emission and decrease in CO_2 emission.

5.5. Smoke and particulate matter (PM)

5.5.1. Effect of alcohol fumigation on smoke opacity and PM emission

Diesel engines are the most remarkable sources of PM emission. PM is the term used for a mixture of solid particles and liquid droplets suspended in the air droplets as dust, dirt and smoke that vary in number, size, shape, surface area, chemical composition and solubility which are originated from a variety of anthropogenic and natural sources. The size distribution of total suspended particles (TSPs) in the ambient air is trimodal, including coarse particles, fine particles, and ultrafine particles. These particles exist in different shapes and densities in the air which are especially relevance to inhalation and deposition, sources, or toxicity [112–114]. PM is highly complex mixture of elemental carbon or soot, adsorbed hydrocarbons and inorganic compounds (sulfates and water, etc.) [115–117]. Smoke opacity is an indirect indicator of soot content in the exhaust gases. Therefore this parameter can be correlated with the fuel's tendency to form particulate matter (PM) during engine operation [111]. Soot particles are formed very early in the combustion process and most are oxidized at very high temperatures. Since alcohol has lower calorific value so alcohol fumigation significantly reduces PM emission. Majority of the authors reported decrease in PM emission in alcohol fumigation mode.

Zhang et al. [91] experimentally investigated the effect of alcohol fumigation in four cylinders in line DI engine using 10%, 20% and 30% fumigation methanol with diesel fuel at the engine speed of 1920 rev/min with five steady conditions. For all fumigation ratios, PM emission decreases compared to diesel fuel. They observed that reduction was more significant at medium load with all percentage of fumigation. About 14–31% reduction was measured with 10% fumigation methanol when reduction was about 27–57% with 30% fumigation ethanol.

Abu-Qudais et al. [79] investigated the comparative effect of ethanol fumigation and ethanol–diesel blend fuel on PM emission. They reported that smoke opacity and soot mass concentration decreased with increasing engine speed. They measured maximum decrease in smoke opacity and soot mass concentration of 48% and 51% for 20% ethanol fumigation whereas for ethanol–diesel blend the maximum reduction was measured as 33.3% and 32.5% at 15% ethanol blend.

The effect of ethanol fumigation on PM emission was experimentally analyzed in pre-Euro I, 4-cylinder by Surawski et al. [80]. Test was conducted following two processes. In the first mode, experiment was conducted at 2000 rpm with full load and in second mode; experiment was conducted at an intermediate speed 1700 rpm with four different loads setting. In both cases neat diesel used having 10 ppm sulfur and ethanol having 0.55% moisture denatured with 1% unleaded petrol. Their results showed that ethanol fumigation significantly reduced PM emission especially at full-load operation during the E40 test. At half or quarter load, PM reduction was not satisfying compared to full-load.

Tsang et al. [87] reported that ethanol fumigation reduces smoke opacity and PM emission compared to diesel fuel. Smoke opacity increases with increasing engine load with all levels of fumigation but no significant change was found at low engine load. At medium and high loads, significant change in smoke opacity reduction was achieved with all levels of fumigation. They measured reduction of smoke opacity by 31%, 56% and 19% at corresponding engine loads of 0.39, 0.58 and 0.70 MPa with 20% ethanol fumigation. 27% reduction was found with all fumigation ratios.

Cheng et al. [92] reported that methanol fumigation reduced smoke opacity and PM emission in comparison with diesel fuel. They found average reduction in particulate mass concentration is about 25% for 10% fumigation methanol. But maximum reduction was 49% at higher level of fumigation.

Zhang et al. [93] experimentally analyzed the effect of 10%, 20% and 30% methanol fumigation on NO_x emission in a naturally aspirated, in line 4-cylinder DI engine. No significant change was found in smoke opacity and PM concentration at low loads but at medium and high engine load condition, remarkable reduction was found compared to diesel fuel. Maximum 58% smoke reduction was found with 30% fumigation methanol at the engine load of 0.58 MPa. The particulate mass concentrations were reduced by 33–43% for the engine load of 0.08 MPa, 27–49% for 0.19 MPa, 30–56% for 039 MPa, 26–61% for 0.58 MPa and 19–34% for 0.7 MPa.

Tsang et al. [89] found that methanol fumigation causes lower PM emission than ethanol fumigation and reduction was 15–32%

and 20–41% for 10% and 20% fumigation methanol and 9–19% and 7–26% for 10% and 20% fumigation ethanol. They also observed that PM decreased with increasing ethanol fumigation like methanol.

Chauhan et al. [84] reported that smoke opacity increased with increasing engine loads and decreased as ethanol fumigation increased. At higher load of 70% and 100%, smoke opacity decreased very quickly up to 14% ethanol fumigation then reduction was lightly. The reason behind this is due to oxygen content increased at higher level of fumigation which causes better combustion resulting in lower opacity.

5.5.2. Summary

Based on the above literature review, it is clear that alcohol fumigation significantly reduces the smoke opacity and PM emission compared to neat diesel fuel. The following reasons can be attributed for the reduction of smoke opacity and PM emission:

(1) There is less diesel fuel consumed with increasing alcohol fumigation since a remarkable part of diesel fuel is replaced by alcohol. Therefore, less diesel fuel is burned in the diffusion mode and combusts together with the homogenous alcohol/air mixture which helps to burn faster and with higher availability of oxygen, leading to a reduction in PM emission.
(2) Alcohol fumigation increases the ignition delay which enhances the mixing of diesel fuel with the alcohol–air mixture that improves air utilization and reduces smoke.
(3) Alcohol is free of aromatics, free of sulfur, has lower C/H ratio than diesel fuel and alcohol also increases the hydrogen content in the mixture, resulting in a reduction in PM emission.

6. Conclusions

Alcohol from renewable and domestic sources is being considered as a viable sustainable source for future fuel supply. Fumigation method represents the most efficient way of using alcohol in diesel engine. Therefore, many researchers are giving their attention to alcohol fumigation for satisfactory engine performance and mitigating of environment pollutants from diesel engine. After testing a large number of different engine technologies and applying various operational conditions the following general conclusion could be drawn to summarize the massive related literatures in alcohol fumigation mode:

(1) When fumigation alcohol is applied to the diesel engine, BSFC increase with the percentage of fumigation alcohol at all engine loads. Around 7–12% increase of BSFC in mass basis has been found in most of the reviewed studies, which is a consequence of the lower calorific value of alcohol.
(2) Alcohol fumigation decreases BTE at low engine loads but there is a little increase in BTE at medium and high engine loads. The decrease in BTE has been found in the range of 5–13% and increase in BTE has been found in the range of 2–9%.
(3) Regarding gaseous emission, alcohol fumigation decreases NO_x emission compared to diesel fuel. NO_x emission is significantly affected by engine loads. The maximum reduction has been found to be 20% compared to pure diesel fuel at lower engine load for 30% fumigation in most of the experiments.
(4) Alcohol fumigation increases the CO and HC emission compared to diesel fuel. The increase in CO emission has been found in the range of 1.00–29.4 g/kWh. On the other hand, increase in HC emission has been found in the range of 0.5–39.05 g/kWh.
(5) Alcohol fumigation significantly decreases the CO_2 emission which is corollary of CO emission reduction.
(6) Alcohol fumigation can substantially reduce smoke opacity and PM emission compared to diesel fuel. The reductions are mainly associated with the reduction of diesel fuel burned in the diffusion mode. The reductions have been found between a wider range of 14–57% at over all engine load conditions.

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